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(71) Applicant(s)
Kvaerner FSSL Limited
(Incorporated in the United Kingdom)
Davy House, Windsor Plaza, 68 Hammersmith Road, LONDON, W14 8YW, United Kingdom

(72) Inventor(s)
David Alfred Jackson

(74) Agent and/or Address for Service
Bowles Horton
Felden House, Dower Mews, High Street, BERKHAMSTED, Herts, HP4 2BL, United Kingdom

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None

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UK CL (Edition O) **G1A ABF ACA ACEF ACFG**
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(54) Abstract Title
Piezo-electric current monitor

(57) Remote monitoring of an electrical signal for example the current flowing through a wire (2) is provided by a system which includes a piezo-electric element (45) bonded to an optical fibre (7) including at least one Bragg grating (6). Changes in the reflecting wavelength of the grating or changes in the path length of an interferometer (42) including the grating are sensed to give an indication of the electrical signal in the wire. The fibre could include a multiplicity of Bragg gratings adapted to reflect substantially different optical frequencies.

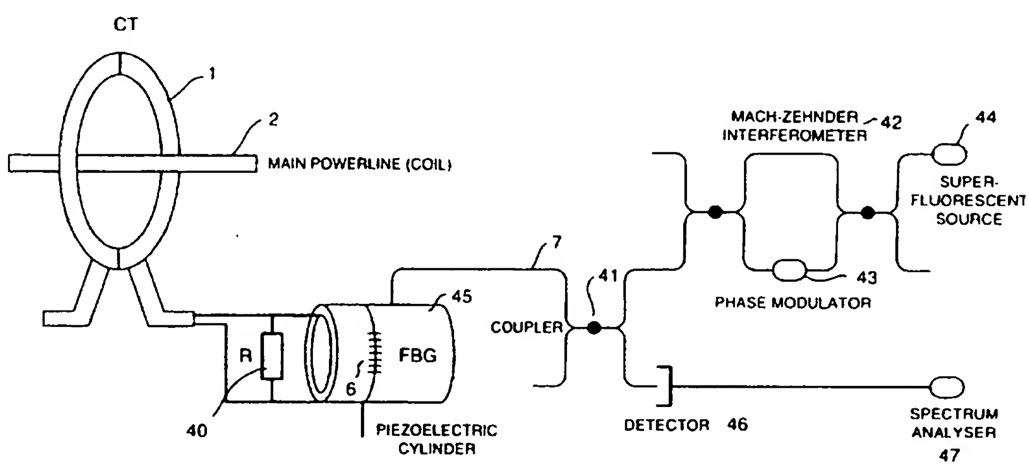

FIG.4

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At least one drawing originally filed was informal and the print reproduced here is taken from a later filed formal copy.

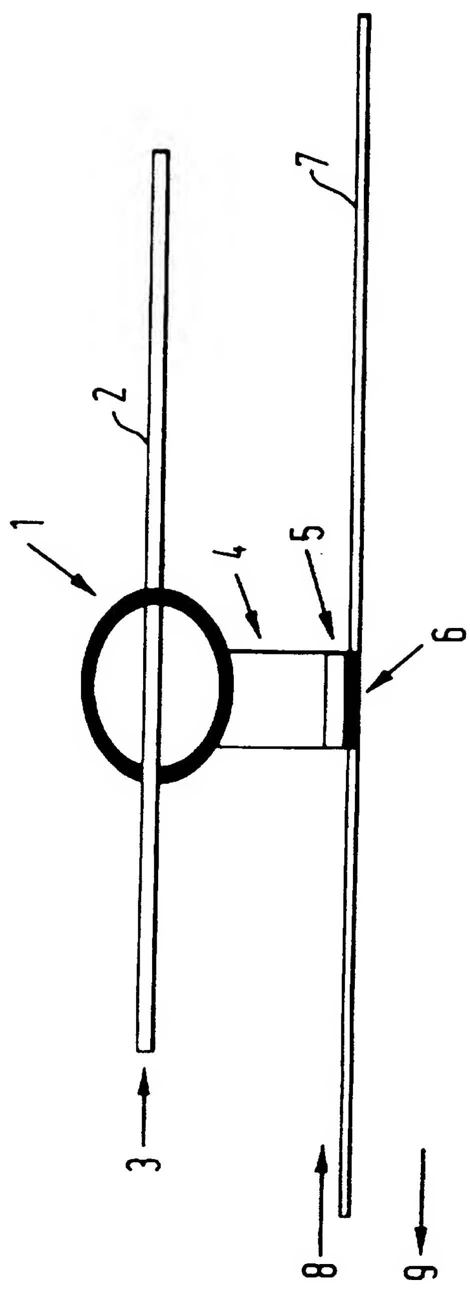

FIG.1

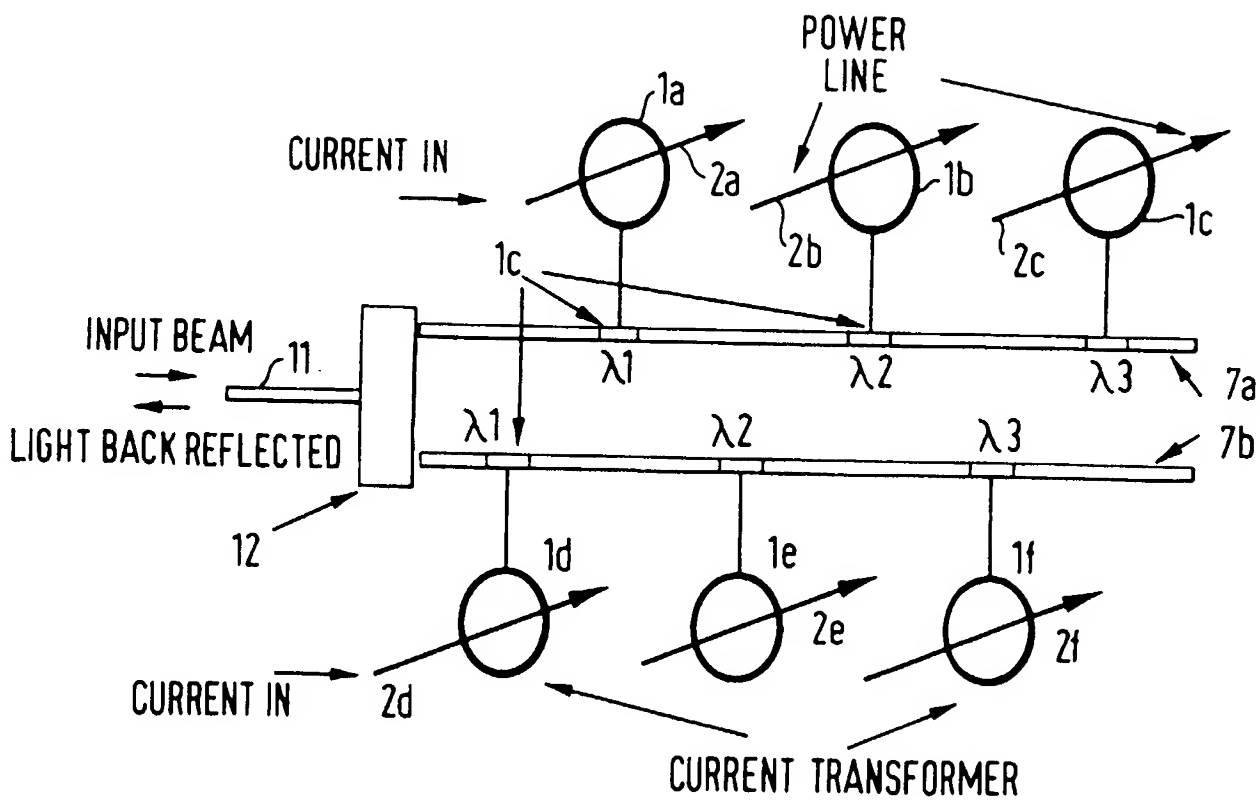
POWER
LINE
CURRENT IN
1a
2a
1b
2b
1c
2c
1c
INPUT BEAM
11
LIGHT BACK REFLECTED
λ1
λ2
λ3
7a
7b
12
1d
1e
1f
2d
2e
2f
CURRENT IN
CURRENT TRANSFORMER

FIG.2

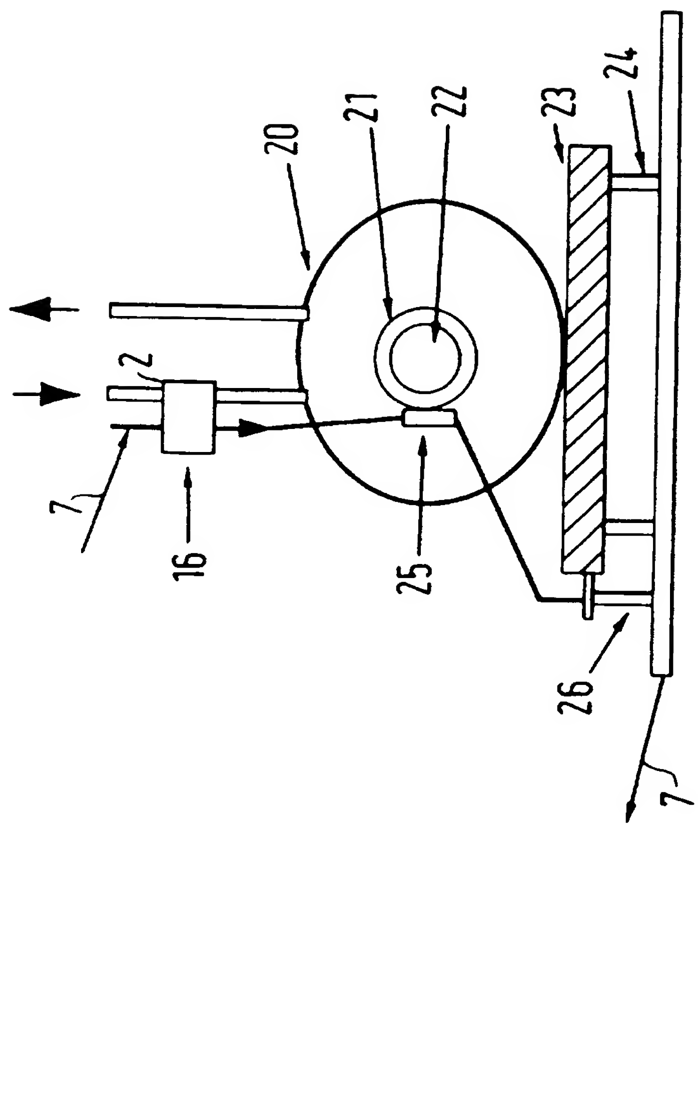

FIG.3

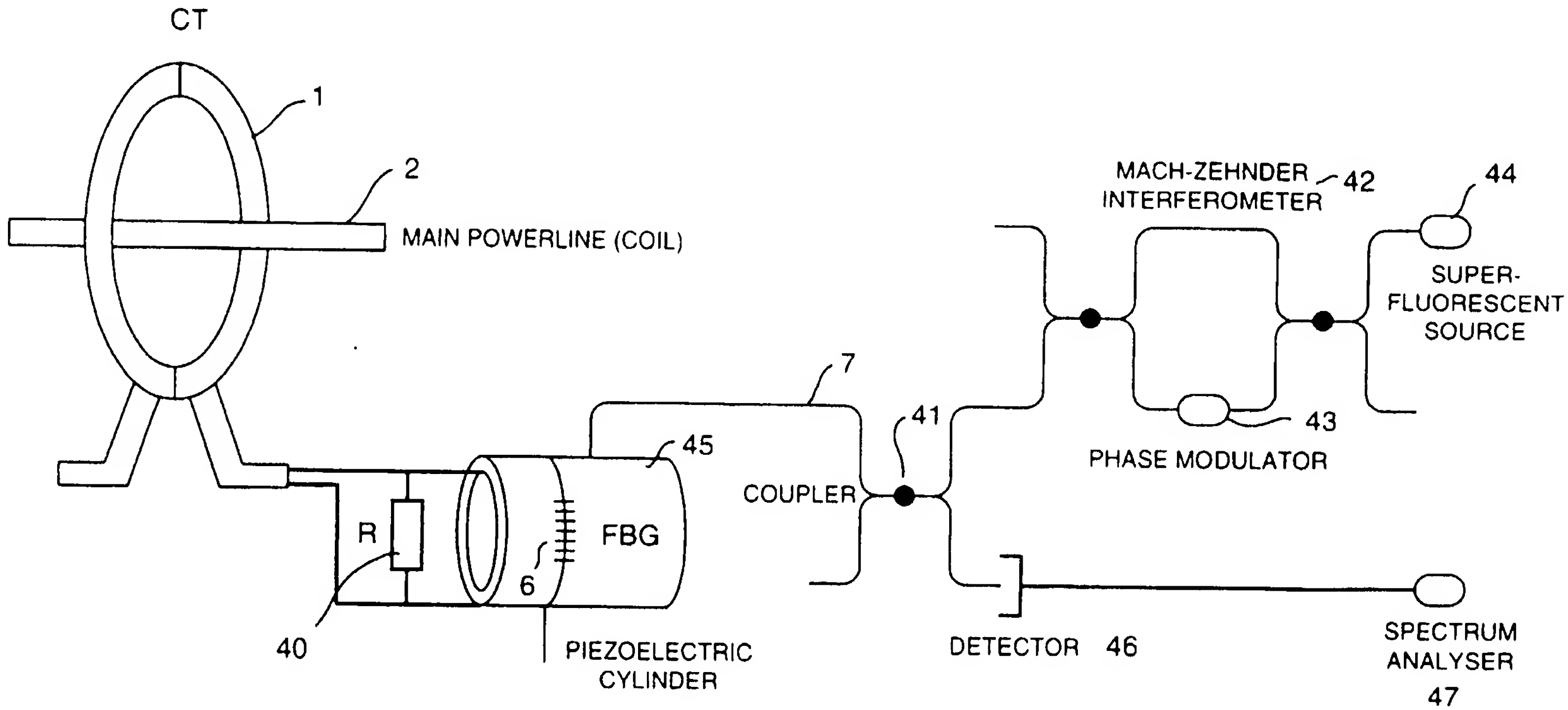
CT
1
2
MAIN POWERLINE (COIL)
R
40
6
FBG
45
PIEZOELECTRIC
CYLINDER
7
COUPLER
41
DETECTOR 46
MACH-ZEHNDER
INTERFEROMETER
42
PHASE MODULATOR
43
44
SUPER-
FLUORESCENT
SOURCE
SPECTRUM
ANALYSER
47

FIG. 4

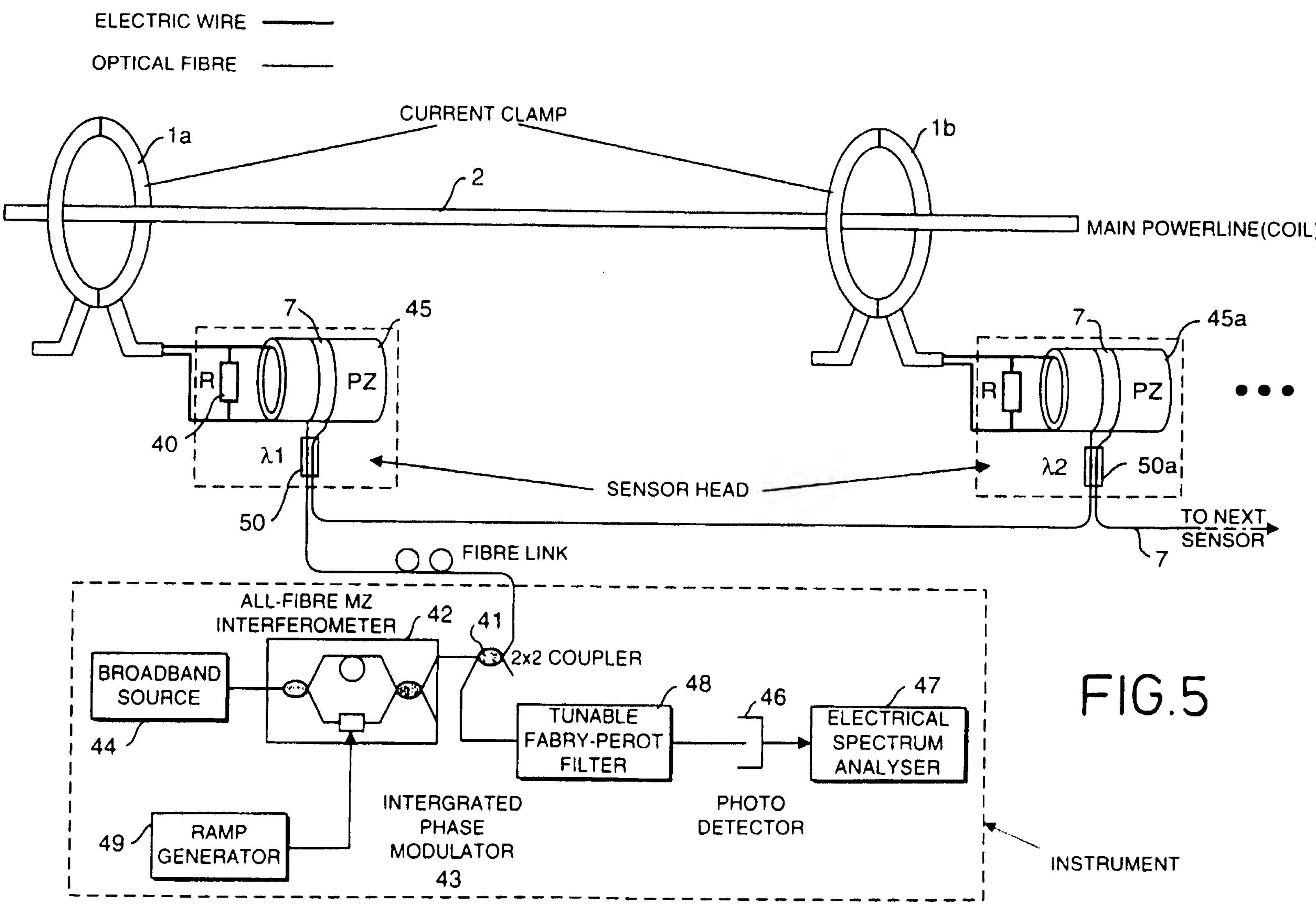
ELECTRIC WIRE
OPTICAL FIBRE
CURRENT CLAMP
1a
1b
2
MAIN POWERLINE(COIL)
7
45
45a
R
PZ
40
λ1
λ2
50
50a
SENSOR HEAD
TO NEXT SENSOR
7
FIBRE LINK
ALL-FIBRE MZ INTERFEROMETER
42
41
2x2 COUPLER
BROADBAND SOURCE
44
48
46
47
TUNABLE FABRY-PEROT FILTER
ELECTRICAL SPECTRUM ANALYSER
PHOTO DETECTOR
49
RAMP GENERATOR
INTERGRATED PHASE MODULATOR
43
INSTRUMENT

FIG.5

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MONITORING ELECTRICAL SIGNALS BY PIEZO-ELECTRIC ADJUSTMENT OF BRAGG GRATINGS

This invention relates to the monitoring of electric currents, such as motor currents, and other electrical signals.

GENERAL BACKGROUND TO THE INVENTION

Bragg gratings incorporated in optical fibres have recently been developed for sensing and communication systems. Such a Bragg grating can be written into an optical fibre at any selected location. Bragg gratings incorporated in optical fibres have been used to detect temperature or strain. The Bragg grating is essentially a permanent periodic density perturbation in the fibre. When the fibre is illuminated by an optical source it reflects light only at a well defined wavelength, determined by the pitch of the periodic density perturbation. If the grating is dimensionally altered, such as by strain or heating, the reflecting wavelength of the grating will change.

SUMMARY OF THE INVENTION

The present invention is based on the concept of detecting an electrical signal by using a piezo-electric element to alter dimensionally an optical structure which is incorporated within an optical fibre and includes at least one Bragg grating in the fibre. In one aspect of the invention, the piezo-electric element may be bonded to the Bragg grating or to the fibre adjacent the Bragg grating. When the piezo-electric element thus disposed is subjected to either a direct or time varying signal it will cause the Bragg grating within the fibre to expand or contract, producing either a static shift or a periodic variation or both in the wavelength which the Bragg grating will reflect. Such a change in the wavelength may be detected by any one of a variety of means, as explained for the sake of example hereinafter.

In another aspect of the invention, a piezo-electric element may be used to transduce a voltage into a phase modulation in a fibre-optic interferometer. A piezo-electric element responsive

to a voltage, which may be developed in correspondence with a current to be monitored, may be coupled to an optical fibre between the ends, defined preferably by Bragg gratings, of a Fabry-Perot interferometer, so that variation in the voltage applied to the piezo-electric element alters the optical path length in the interferometer. This variation in path length may be exhibited by a phase change which may be measured by determining the amplitudes of side band frequency components obtained from the interferometer and observed on an electrical spectrum analyser. Alternatively a phase-lock loop may be used to produce a scaled electrical version of the original signal.

STATE OF THE ART

It is known from EP-B-0556247 to apply different longitudinal stresses to vary the stress in an optical fibre during the writing of a Bragg grating in the fibre by means of a piezo-electric element which may be a cylinder around which the fibre is wrapped or may be a cladding on the fibre.

BRIEF DESCRIPTION OF THE DRAWINGS

The accompanying drawings illustrate by way of example the basic concepts of the invention and several practical systems for putting the invention into practice. Various objects and preferred features of the invention will be apparent from the detailed description, for which:

Figure 1 is a schematic diagram illustrating a basic form of a transducer for use in the invention;

Figure 2 is a schematic diagram of an embodiment of the invention;

Figure 3 is an illustration of another embodiment of the invention;

Figure 4 is a schematic diagram of one preferred sensing system according to the invention; and

Figure 5 is a schematic diagram of another embodiment of a sensing system according to the invention.

DETAILED DESCRIPTION

As indicated previously, one aspect of the invention concerns the detection of an electric current by using a piezo-electric element which is bonded to an in-fibre Bragg grating. Methods of production of a Bragg grating in an optical fibre are well known and need not be described in detail. There are several ways in which a piezo-electric element may be juxtaposed with a fibre Bragg grating. The grating may be bonded to a ceramic element which is in the form of a cylinder or rod and which exhibits a piezo-electric effect. Alternatively, a piezo-electric element in the form of a heat-shrinkable tube may be placed over a fibre Bragg grating. The primary coating of the fibre may be removed beforehand. Heat may be applied to the tube such that it collapses onto the fibre at the location of the grating, thereby forming an intimate bond. When a current or voltage is applied to the piezo-electric element the central wavelength of it will vary in response to applied signals. Another option is to produce on the fibre a piezo-electric element by means of a chemical deposition method.

Figure 1 illustrates a basic sensing system including a combined piezo-electric and fibre Bragg grating as just discussed. A current transformer 1 is linked by a conductor 2 carrying an electrical current 3. The current transformer produces on output conductors 4 an output signal which is directly proportional to the current in conductor 2. The output of the current transformer may be converted to a voltage by way of a resistor and the signal developed across the resistor may be used to drive a piezo-electric element 5 which is bonded to a Bragg grating 6 incorporated within an optical fibre, preferably a monomode fibre, 7. The grating may be illuminated by a broadband optical signal, represented by the arrow 8. The wavelength of the light 9 reflected back from the grating depends on the signal applied to the piezo-electric element. The alteration in wavelength may be remotely sensed by a variety of methods which will be discussed later.

If the current carrying wire is at a high potential, considerable electrical insulation may normally be required in the transformer between the primary and secondary coils. Such insulation tends to be large, heavy and to occupy a large volume. An optical fibre is a natural insulator and accordingly the level of electrical insulation required is low. In turn this means that the current transformer may be small, lightweight and inexpensive.

Figure 2 illustrates an advantageous development of the basic system. In the system shown in Figure 2, fibre Bragg gratings are disposed so that different currents can be measured using wavelength and spatial multiplexing. More particularly, there is a multiplicity of power lines 1a, 1b...1f, each of which is coupled by a respective one of the current transformers 2a-2f to a respective piezo-electric element in a respective transducer 10 each of which is constituted by a piezo-electric element and fibre grating as described with reference to Figure 1. In Figure 2, by way of example, three gratings are disposed in an optical fibre 7a and three more gratings are disposed in an optical fibre 7b. Light from a broadband source is propagated towards the optical structure represented by fibres 7a and 7b along a fibre 11 which is coupled to the fibres 7a and 7b by means of a distributor 12. The various gratings 10 are written so as to reflect different wavelengths of light. Thus the various sensors represented by each current transducer and the associated piezo-electric element and Bragg grating can operate independently and the optical information representing the current in the various power lines may be multiplexed in the form of a multiplicity of optical frequencies in the light reflected back along fibres 7a and 7b, through distributor 12 and back along optical fibre 11.

Equipment such as shown in Figure 2 may be used, for example, in the monitoring of a multiplicity of currents in motors or other electric equipment operating in sub-sea hydrocarbon extraction equipment.

It is generally important to ensure that when, for example, the sensing system is used to sense a motor current, any vibration caused by the motor is not coupled to the piezo-electric element. However, in general, vibrationally induced noise may be reduced using differential detection whereby two fibre Bragg gratings are used rather than a single grating to monitor any particular current.

The signal produced by a transducer comprising a Bragg grating and piezo-electric element as described in the foregoing may be multiplexed with other Bragg gratings in the same fibre. Figure 3 illustrates a hybrid system in which optical signals representing a monitored motor current may be multiplexed with optical systems obtained from other Bragg gratings employed to measure other quantities. In Figure 3, an optical fibre 7 is used to convey multiplex signals representing various quantities associated with the operation of a motor 20. The main motor current passes through a conductor 2. This current is monitored using a transducer 10, which includes a current transformer and an associated piezo-electric element bonded to a fibre Bragg grating within the fibre 7 as previously described with reference to Figure 1.

The motor has a bearing 21 and shaft 22. It is mounted on a base 23 which has flexible mounts 24.

The temperature within the motor is sensed by a further Bragg grating 25. This responds directly to temperature and does not need any associated piezo-electric element. However, the Bragg grating 25 preferably has a centre wavelength which is separated from the centre wavelength of the Bragg grating within transducer 10. Likewise, another Bragg grating 26 within the fibre and having an ordinary centre wavelength different from those of the other Bragg gratings within fibre 7 is used to sense vibration at the base of the motor.

The fibre 7 may extend to the next motor which may have associated with it various other Bragg gratings whereby information on that motor's performance may be multiplexed along the same fibre 7 with the information on the performance of the motor 20.

The invention may also be employed to interrogate all the currents in a poly-phase power line, employing respective transducers of the kind shown in Figure 1 for sensing each current in the poly-phase system.

Figure 4 illustrates in more detail a complete sensing system including the basic transducer, a current transformer, the voltage developed across the secondary transformer being converted

into a phase modulation in a fibre-optic interferometer. The Bragg grating within the fibre is used to provide a modulated optical signal within the interferometer.

More particularly, a current transformer 1 transforms the current flowing through a main power line 2 into a secondary current which is converted into a voltage by means of a high wattage resistor 40. The voltage is applied directly to a piezo-electric cylinder 45 around which is looped an optical fibre 7 which includes a fibre Bragg grating 6 which is bonded to the cylinder 45. At low signal levels, typically less than fifty volts for alternating signals, the variation in the diameter of the cylinder 45 is proportional to the applied voltage signal over more than five orders of magnitude for frequencies less than the first mechanical resonance. Thus the variation in the strain applied to the grating 6 is linearly related to the current induced in the secondary circuit of the current transformer.

In the system shown in Figure 4, the optical fibre 7 is coupled by way of an optical coupler 41 to an unbalanced Mach-Zehnder interferometer 42 which includes a phase modulator 43 and is coupled to a super-fluorescent source. Typically the source has a centre wavelength of 1545 nanometres and a bandwidth of 40 nanometres.

The coupler 41 also couples light from the source and backscattered from the grating 6 to a detector 46 which is coupled to a spectrum analyser 47.

Signal detection in the system shown in Figure 4 may be achieved using pseudo-heterodyne processing, for example by applying a ramp modulation to the phase modulator 43. Provided that the optical path difference between the arms of the Mach-Zehnder interferometer is longer than the coherent length of the source and shorter than the effective coherent length of the light reflected back from the grating 6, interference signals are observed at the detector. Thereby, strain-induced changes in the reflected wavelength induce a phase modulation of the carrier signal induced by the phase modulator and may be measured by determining the amplitudes of the sideband frequency components observed on the spectrum analyser. These frequency components may be optimized by adjusting the path length so that the bandwidth of the channel spacing incident on the grating is matched to the grating's line width. By way

of example, the grating may have a peak reflecting wavelength of 1548.6 nanometres, a peak reflectivity of 90° and a line width of 0.2 nanometres. Typically, the phase modulator may be driven at a frequency of 1 kilohertz.

Instead of the phase modulator, an acousto-optic may be used. In that case, true heterodyne signal processing may be employed.

Figure 5 illustrates a more sophisticated system which employs a Fabry-Perot interferometer which is preferably defined by two Bragg gratings written into an optical fibre, one of the gratings having a high reflectivity and the other a moderate reflectivity, such as reflectivities of 100° and 38° respectively.

In the system shown in Figure 5, a current transformer 1a transforms current passing through a conductor 2 into a secondary current which is applied to a resistor 40 in order to develop a corresponding voltage as described with reference to Figure 4. The developed voltage is applied to a piezo-electric cylinder 45. An optical fibre 7 has written into it two Bragg gratings at spaced apart locations. These two gratings are shown side by side as the element 50. Part of the fibre connecting the gratings is wrapped around the cylinder 45. At a low signal level, the variation in the diameter of the cylinder is linearly proportional to the amplitude of the applied voltage over more than five orders of magnitude for frequencies less than the first mechanical resonance, which is typically a few tens of kilohertz. Light from a super-fluorescent source 44 or other broadband source, preferably with a bandwidth of about 40 nanometres extending from 1530 to 1570 nanometres, may be launched into an unbalanced Mach-Zehnder interferometer 42. In the interferometer 42, a serrodyne or ramp modulation is applied to a phase modulator 43 by a ramp generator 49 to generate an electrical phase carrier for pseudo-heterodyne signal processing. The optical path difference between the two arms of the interferometer 42 may be set at, for example, two metres, a distance which is much longer than the coherent length of the light source and the effective coherent length of the light backscattered from the fibre Bragg gratings. Interference signals may be observed at the detector when the optical path distance of the Mach-Zehnder interferometer 42 is matched to

that of the in-fibre Fabry-Perot interferometer, with a fibre length of one metre. The phase change within the Fabry-Perot interferometer induced by changes in the current 2 can be measured by determining the amplitudes of sideband frequency components on an electrical spectrum analyser or by means of a phase-locked loop. Wavelength division multiplexing may be exploited for selection of the various signals by tuning a tunable Fabry-Perot filter 48 disposed between the coupler 41 and the photo-detector 46 which is coupled to the spectrum analyser 47. By way of example, the Fabry-Perot interferometers 50 and 50a in Figure 5 may have a bandwidth of 0.2 nanometres and central wavelengths of 1530.5 nanometres and 1534 nanometres respectively.

A system shown in Figure 5 may provide a highly linear characteristic relating change in centre frequency to changes in the sensed current. It may also be arranged so that substantially no crosstalk exists between the Fabry-Perot interferometers. The system may be substantially insensitive to vibration because the sensing interferometer is a Fabry-Perot interferometer and interference can occur only within the cavity rather than throughout the whole length of the fibre.

CLAIMS

1. A method of monitoring an electric current, comprising:

subjecting a piezo-electric element to a signal which varies according to said current;

producing by means of said element a dimensional change in a optical structure which is incorporated in an optical fibre and includes at least one Bragg grating;

launching an optical signal along the fibre towards said optical structure; and

monitoring change in light reflected along the fibre by said structure.

2. A method according to claim 1 wherein the piezo-electric element is closely adjacent said grating and is disposed to vary a dimension thereof to alter correspondingly the wavelength of light which the grating reflects along the fibre.

3. A method according to claim 1 wherein the optical structure is a Fabry-Perot interferometer constituted by two Bragg gratings spaced apart along the length of the fibre and the said piezo-electric element is coupled to the fibre between the gratings.

4. A method according to any foregoing claim wherein the fibre includes a multiplicity of Bragg gratings which are adapted to reflect substantially different optical frequencies.

5. Apparatus for monitoring an electrical signal, comprising:

an optical fibre incorporating an optical structure which includes at least one Bragg grating within the fibre and is adapted to reflect along the fibre light at a narrowly defined wavelength;

a piezo-electric element which is disposed to respond to said signal to vary a dimension of said grating and thereby to vary the said wavelength; and

means for monitoring variation in said wavelength to provide an indication of change in said signal.

6. Apparatus for monitoring an electrical signal, comprising:

an optical fibre incorporating an Fabry-Perot interferometer constituted by two Bragg gratings within and spaced apart along the fibre;

a piezo-electric element which is adapted to respond to said signal and is coupled to the fibre between said gratings to vary the optical path length between the gratings in response to said electrical signal; and

means for monitoring phase variation in light reflected by the interferometer to provide an indication of change in said electrical signal.

The Patent Office

Application No:	GB 9716931.2	**Examiner:**	C. R. Brain.
Claims searched:	ALL	**Date of search:**	14 November 1997

Patents Act 1977
Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.O): G1A (ABF, ACA, ACEF, ACFG)

Int Cl (Ed.6): G01D 5/26; G01R 15/24, 29/08, 29/12

Other: Online: WPI

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
	NONE	

X Document indicating lack of novelty or inventive step	A Document indicating technological background and/or state of the art.
Y Document indicating lack of inventive step if combined with one or more other documents of same category.	P Document published on or after the declared priority date but before the filing date of this invention.
& Member of the same patent family	E Patent document published on or after, but with priority date earlier than, the filing date of this application.